NORMALLY-OFF SEMICONDUCTOR DEVICES AND METHODS OF FABRICATING THE SAME

STATEMENT OF U.S. GOVERNMENT INTEREST

[0001] This invention was made with Government support under Contract No. N00014-05-C-226 awarded by the Office of Naval Research. The Government has certain rights in the invention.

FIELD OF THE INVENTION

[0002] The present invention relates to semiconductor devices and, more particularly, to transistors and related methods.

BACKGROUND OF THE INVENTION

[0003] There is a high level of interest in wide bandgap semiconductor materials such as silicon carbide (2.996 eV for alpha SiC at room temperature) and the Group III nitrides (e.g., 3.36 eV for GaN at room temperature) for high power, high temperature and/or high frequency applications. These materials, typically, have higher electric field breakdown strengths and higher electron saturation velocities as compared to gallium arsenide and silicon.

[0004] A device of particular interest for high power and/or high frequency applications is the High Electron Mobility Transistor (HEMT), which is also known as a modulation doped field effect transistor (MODFET). These devices may offer operational advantages under a number of circumstances because a two-dimensional electron gas (2-DEG) is formed at the heterojunction of two semiconductor materials with different bandgap energies, and where the smaller bandgap material has a higher electron affinity. The 2-DEG is an accumulation layer in the undoped ("unintentionally doped"), smaller bandgap material and can contain a very high sheet electron concentration in excess of, for example, 10^{13} carriers/cm^2. Additionally, electrons that originate in the wider-bandgap semiconductor transfer to the 2-DEG, allowing a high electron mobility due to reduced ionized impurity scattering.

[0005] This combination of high carrier concentration and high carrier mobility can give the HEMT a very large transconductance and may provide a strong performance advantage over metal-semiconductor field effect transistors (MESFETs) for high-frequency applications.

[0006] High electron mobility transistors fabricated in the gallium nitride/aluminum gallium nitride (GaN/AlGaN) material system have the potential to generate large amounts of RF power because of the combination of material characteristics that includes the aforementioned high breakdown fields, their wide bandgaps, large conduction band offset, and/or high saturated electron drift velocity. In addition, a major portion of the electrons in the 2-DEG is attributed to polarization in the AlGaN. U.S. Pat. No. 6,316,793, to Sheppard et al., which is commonly assigned and is incorporated herein by reference, describes a HEMT device having a semi-insulating silicon carbide substrate, an aluminum nitride buffer layer on the substrate, an insulating gallium nitride layer on the buffer layer, an aluminum gallium nitride barrier layer on the gallium nitride layer, and a passivation layer on the aluminum gallium nitride active structure.

[0007] A HEMT can be normally-off or normally-on. Normally-off operation may be desired in transistors used as high voltage power switches, for safety reasons. Normally-off operation may also simplify bias circuitry when transistors are used in RF power amplifiers. Conventional high performance GaN power switch transistors and RF transistors are typically normally-on. Conventional normally-off HEMTs have typically resulted in devices having high on-state resistance, slow switching speed, and/or unstable device characteristics. Some of these conventional devices will be discussed below.

[0008] Conventional methods may include a Fluorine treatment after etching the gate. In particular, an AlGaN surface in the gate region may be exposed to a Fluorine-containing plasma prior to gate metallization. As discussed in *High-performance enhancement-mode AlGaN/GaN HEMTs using fluoride-based plasma treatment* by Cai et al. (IEEE Electron Device Letters, Vol. 26, No. 7, p. 435, 2005), the threshold voltage of the device can be shifted to positive values (normally-off) by Fluorine plasma exposure. This method has been adapted to GaN power switch transistors as discussed in, for example, *High-Breakdown Enhancement-Mode AlGaN/GaN HEMTs with Integrated Slant Field-Plate* by C. S. Suh et al., (Proceedings from IEEE International Electron Device Meeting 2006, p. 911). When these methods are used, the threshold voltage may not be stable under stress and may shift toward more negative values. Furthermore, the threshold voltages achieved may be barely positive. To account for sub-threshold leakage, process variability, and noise immunity in applications, Vt>+1V is typically desired.

[0009] Further conventional devices may include a P-type AlGaN or GaN cap. In particular, P-type doped material (GaN or AlGaN) may be formed on an upper surface of the AlGaN barrier layer in the gate region. As discussed in *A Normally-off AlGaN/GaN Transistor with RonA*=2.6 mΩcm2 and BVds=640*V using Conductivity Modulation* by Y. Uemoto et al (Proceedings from IEEE International Electron Device Meeting 2006, p. 907), these devices may have low on-resistances and high breakdown voltages. However, since p-type doping in GaN and AlGaN typically does not have a shallow acceptor level, charging and depletion of the acceptors during normal device operation may be too slow to respond at MHz switching speeds. This can result in increased dynamic on-resistance when the device is operated at high switching speeds.

[0010] Conventional MOSFETs may be fabricated from an unintentionally doped GaN film. As discussed in, for example, 250*C operation normally-off GaN MOSFETs* by Y. Niiyama et al. (Solid-State Electronics vol. 51, p. 784, 2007), these devices closely mimic a Si MOSFET structure. In particular, source and drain contacts are formed on n$^+$ implanted regions. A positive gate bias above the threshold voltage may induce an electron inversion layer in the p-type buffer (or semi-insulating buffer). The mobility of the inversion layer may be low due to interface scattering, which may lead to a high on-state resistance of the device.

[0011] It is understood that with a precisely controlled etch rate, an AlGaN layer that is originally around 250 Å could be etched leaving about 25 Å in the gate region. Depositing gate metal on this thin remaining AlGaN layer may produce a normally-off device. This process is extremely sensitive to the recess etch depth, and is therefore not practical.

[0012] Recess etching into a double channel structure is discussed by M. Kuraguchi et al., (Phys. Stat. Sol. (a) Vol.